Environmental Protection Report

REPORT ON U.S. STUDY TOUR OF ENGINEERED WETLANDS FOR THE TREATMENT OF WASTE WATER AND MINE DRAINAGE, MARCH 1992

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Date: 1st July, 1992.

Metal Wetland

Street sculpture, Boston, Massachusetts.

NRA REPORT ON US MINE WATER TREATMENT STUDY

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EXECUTIVE SUMMARY

During the period 15 to 23 March, 1992, a study tour of passive water treatment schemes within North America was undertaken by the NRA. The tour formed part of a detailed consultants' appraisal of technologies potentially suitable for transfer to Wheal Jane. This report documents the main objectives, observations, lessons learnt and the wider implications of passive treatment system.

The tour was structured to provide opportunities to examine a variety of systems specifically designed to deal with high flow, high metals loading and acidity. No single system observed will meet fully the combined flow and water quality encountered at Wheal Jane. The study provided insights into system design through to commissioning and operation, and illustrated the potential for development of an integrated approach to treatment of mine water drainage from Wheal Jane.

Wider implications for other mine and waste water problems within the United Kingdom are briefly addressed.

NRA REPORT ON US STUDY TOUR

1.0 INTRODUCTION

1.1 Background

The study tour of waste water treatment facilities, acid mine drainage remediation and research projects described in this report forms part of a project undertaken by consultants Arthur D. Little and Marcus Hodges Environment Ltd. The primary focus of the consultants' study was to provide an independent assessment of passive treatment technologies potentially suitable for transfer to Wheal Jane. The overall project is now complete and findings are documented in Arthur D. Little report No. 40922. This short report describes the sites visited and meetings attended, and sets out the key lessons learnt and the implication for the United Kingdom.

1.2 Objectives

The principal objective of the study tour was to provide the opportunity for NRA members of the project team to observe first-hand previously short-listed candidate technologies. The visit also offered the opportunity to discuss in detail with site operators, regulators and design staff the difficulties, shortfalls and operational limitations of specific systems.

The tour was structured to enable observations of a variety of technologies potentially suited to flow control, acidity and metals regulation. It was necessary to visit metalliferous and coal mining regions to observe acidity and metals control. Large scale flows comparable with Wheal Jane are currently only handled by municipal water treatment schemes.

1.3 Schedule

The study tour was organized and led by S. Foster (ADL US). Project Team members taking part were C. V. M. Davies (NRA SW), R. M. Hamilton (NRA SW) and N. A. Postlethwaite (MHE). D. Hammer of the Tennessee Valley Authority was present for much of the tour.

In order to take full advantage of the site access negotiated by US members of the project team, a comprehensive itinerary was followed. (See Figure 1.)

<u>Sunday, 15th March, 1992.</u>

* Study tour team rendezvous in Orlando, Florida.

Monday, 16th March.

* 07:00 hrs Meet Don Hammer (Tennessee Valley Authority)
* 07.30 hrs Travel to Iron Bridge Treatment Plant
* 08:00 hrs Arrive at Iron Bridge Treatment Plant
  Carry out site inspection
* 12:00 hrs Leave Iron Bridge to travel to Lakeland Wetlands System
* 13:30 hrs Commence tour of Lakeland Wetlands System
* 15:30 hrs Leave site to travel to Orlando
* 17:20 hrs Leave Orlando Airport
* 19:32 hrs Arrive Pittsburgh

Tuesday, 17th March.

* 06:45 hrs Travel to US Bureau of Mines
* 07:00 hrs Meet Bob Nairn at US Bureau of Mines
* 09:30 hrs Visit Howe Bridge
* 11:00 hrs Visit REM and Morrison Sites
* 15:00 hrs Depart Morrison site to Airport
* 17:30 hrs Depart Pittsburgh to Minneapolis, Montana
* 19:35 hrs Depart Minneapolis to Fargo ND

Wednesday, 18th March.

* 07:30 hrs Charter Flight to Hillsboro
* 08:30 hrs Visit American Crystal Sugar Wetland Scheme
* 11:00 hrs Leave Hillsboro
* 12:00 hrs Arrive Minot ND, visit Minot Wetlands site
* 15:00 hrs Leave Minot Wetlands site
* 16:10 hrs Depart Minot to Minneapolis
* 18:50 hrs Depart Minneapolis to Denver
* 19:50 hrs Arrive Denver

Thursday, 19th March.

* 09:00 hrs Meet Ron Cohen at Colorado School of Mines
* 10:00 hrs Arrive Big Five Tunnel Project
* 11:30 hrs Tour Central City Mines District (Argo Tunnel, Quartz Hill etc.)
* 13:30 hrs Meet with research workers to discuss AMD research

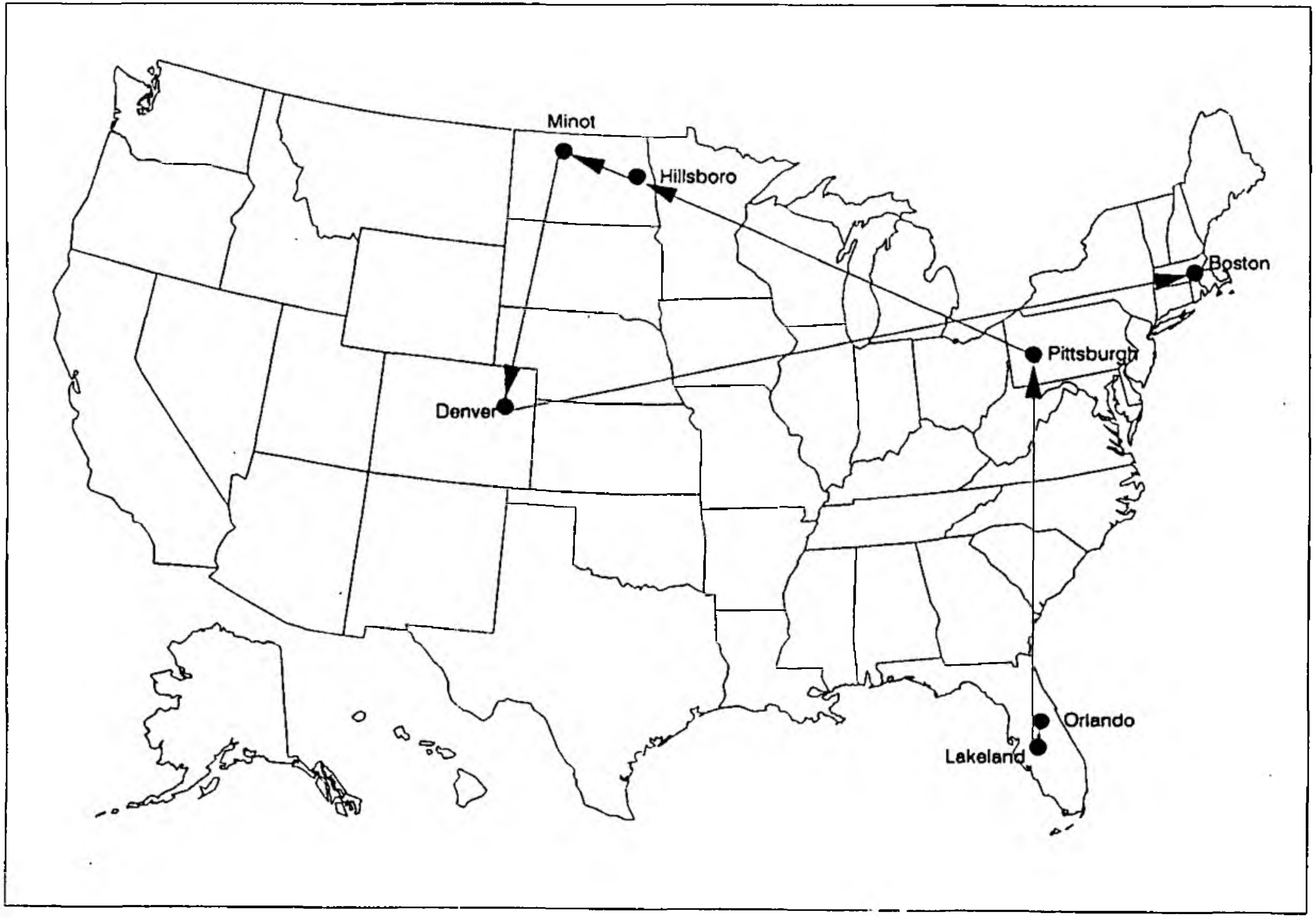
Friday, 20th March.

* 09:00 hrs Meet with Holly Fliniau, EPA Region 8.
* 13:30 hrs Meet with John Gormley - Knight Piésold

Monday, 23rd March.

* 09:00 hrs Meeting at ADL Cambridge, Massachusetts
  Depart Boston to England

Figure 1. Route of United States Study Tour.



2.0 SITE VISIT AND MEETING SUMMARIES

2.1 City of Orlando, Florida, Easterly Wetlands Reclamation Project

2.1.1 Introduction

Initial discussions were held with Dr. Tom Lothrop (Director of Environmental Services), Mrs. Elizabeth Skene (Assistant Bureau Chief) and Mr. Bill Allman (Plant Manager) at the Iron Bridge Water Pollution Control Facility. This is a large sewage treatment works which, in the mid 1980's was rapidly approaching design capacity. Further discharge to the Little Econlockhatchee River was not permitted. The Orlando Easterly Wetlands were created to remove nutrients from increased effluent from the expanded Iron Bridge plant, prior to discharge, eventually, to the St. Johns River. An additional objective was the provision of wildlife habitat. Mrs Skene and Mr Allman accompanied us on a tour of the wetlands.

2.1.2 System Design

The wetlands occupy 1,220 acres on a 1,640 acre site which previously was cattle pasture. Figure 2 shows a plan of the site. Seventeen cells were created by the construction of 18 miles of berms, with simple weir structures to control flow distribution, depth and retention time. The winning of berm material allowed the construction of an 80 acre lake. Cells 1 to 12, in total 420 acres, were developed as deep wet prairie and planted mostly with two hardy species with high growth rate and nutrient removal potential. Cells 13 to 15, comprising 380 acres, were developed as a shallow mixed marsh to provide further nutrient removal. Ten species were planted. A further 60 have subsequently established themselves. Cells 16 and 17, in total 400 acres, consist of a hardwood swamp and the lake, primarily to provide final settlement and wildlife habitat.

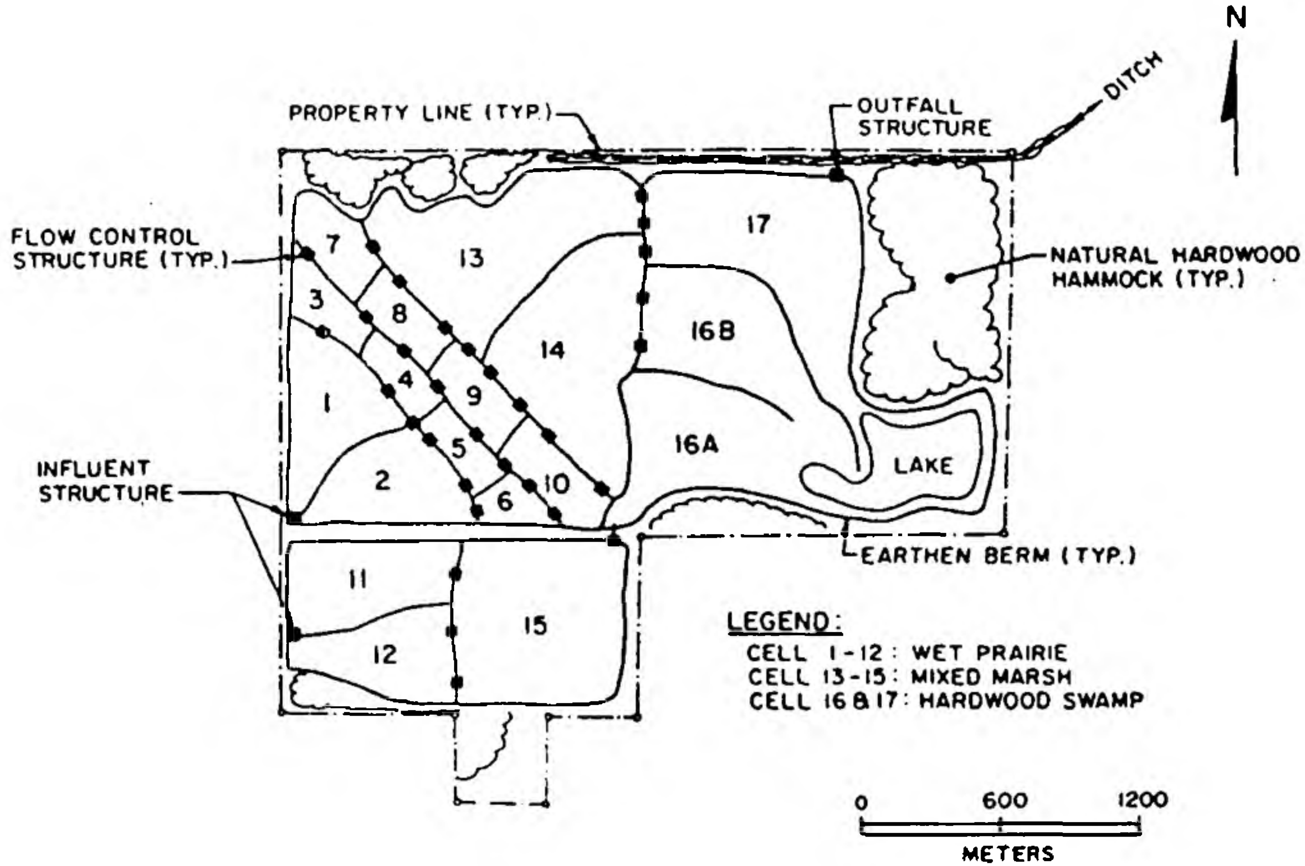
The wetlands are 15 miles from the Iron Bridge plant. Low pressure pumps deliver effluent through a 48" pre-stressed concrete pipeline. Delivery to the wet prairie is through a simple surge chamber, the exit channel having bank revetments for only a few yards. All flow is across the surface and there is a limited attempt to produce an even spread. The design average flow is 20 mgd. Expected concentrations in the inflow water are 6 mg/l total nitrogen and 0.75 mg/l total phosphorous. Removal rates of 1.5 kg/ha/day of nitrogen and 0.15 kg/ha/day of phosphorous were expected.

2.1.3 Constraints

The discharge from the wetlands was required to pass through another area of hydraulically altered wetlands to restore them, but without significantly and negatively altering existing wetland communities. These conflicting demands were resolved when the owner of the downstream wetland accepted that changes to community structure are not necessarily negative.

The development of tourism at the Orlando Easterly Wetlands is limited by the retention of hunting rights by the previous landowner.

Figure 2. City of Orlando man-made wetlands system.



2.1.4 Performance

Recent average inflow is 13 mgd, up to a peak of 35 mgd. About 8 to 9 mgd leave the system, the losses being due to evapotranspiration. The retention period is about 30 to 40 days. Storm events appear not to stress the system. There has been no requirement so far for cell maintenance. Final effluent quality is good, being about 1 mg/l nitrogen and 0.15 mg/l phosphorous. Most of the nutrient removal occurs within the first few cells in about 10% of the system. There has been no evidence of a moving front of high phosphorous concentrations. Dissolved oxygen concentrations can be low. A passive aeration system is provided to ensure that consent conditions are met. This tends to create foaming, due to the presence of humic acids in the effluent.

2.1.5 Additional Benefits

The wetlands are extremely attractive to wildlife. There are now 150 species of plants on site, with 141 species of birds, 22 of reptiles, 16 of mammals, 16 of fish, and 8 of amphibians. Nine miles of walking trails have been developed with information boards and route markers. Promotional material is available to the public, although the facility is not vigorously publicised and hence is under-used.

2.1.6 Costs

The total capital cost was $25 million (about £14.7 million). The maintenance contract costs $200k/year (about £118k/year) of which about 50% is for monitoring, with the remainder for weed control, fees and reports.

2.1.7 Summary

The system is operating at less than design capacity. It is successful, despite the apparently simple approach to flow control. The additional benefit of attractiveness to wildlife is spectacular. The sub-tropical location is a bonus. Surface sheet flow is not considered appropriate for dealing with acid mine discharges. However, the modular design gives a flexibility of operation which is likely to be needed at a Carnon Valley wetland.

2.2 City of Lakeland, Florida, Wetlands Project

2.2.1 Introduction

In 1983, the US Environmental Protection Agency denied the city of Lakeland's request to renew its discharge consent from the Glendale sewage treatment works to the eutrophic Banana Lake. Consultants recommended the development of a wetland several miles from the city as additional treatment and an alternative discharge route. Applications for grants were made in 1984 and 1985. Construction took one year with the system being commissioned in 1987, just before the temporary operating permit ran out. Dave Hill (Environmental Scientist) conducted us on a tour of the wetlands.

2.2.2 System Design

The wetlands occupy about 1,250 acres on a 1,640 acre site previously used as clay settling ponds by the phosphate mining industry. The clay had formed a relatively impermeable liner to the shallow ponds, which had been invaded by cat-tails (Typha latifolia) and willow (Salix spp.). Figure 3 shows a plan of the site. Limited changes to the existing system included construction of a vegetated overland flow cell prior to the first wetland cell, improvements to the berms, construction of a distribution system, and enhancement of planting.

The overland flow cell was designed to reduce Total Kjeldahl Nitrogen (TKN) in an attempt to limit the health risks associated with culicene mosquitoes, the occurrence of which is reported to be positively correlated with high TKN concentrations in vegetated lagoons. Cells 2 to 5 are shallow, with mixed vegetation. Flow then proceeds through a series of increasingly deep lakes before discharging to a tributary ditch of the Alafia River.

Inflow is through a six mile pipeline and a simple surge chamber. Delivery from cell to cell is through substantial weir structures and lined distribution ditches, which have simple weir structures every 30 yards or so. This is designed to provide even sheet surface flow. Although designed for 14 mgd, only 10 mgd are permitted. Inflow quality was expected to be 20 mg/l BOD, 20 mg/l suspended solids and 8 mg/l ammonia.

2.2.3 Constraints

Between 4 and 5 mgd of the output from Lakeland's sewage treatment works are used by the local power plant for cooling purposes. However, during power plant downtime, this effluent must be diverted to the wetlands, where inflow can vary between 5 and 10 mgd. Effluent limits are 5 mg/l BOD, 10 mg/l suspended solids, 1 mg/l ammonia and 2.5 mg/l TKN.

2.2.4 Performance

Recent inflows have been about 8.5 mgd with 7 mgd leaving the system.

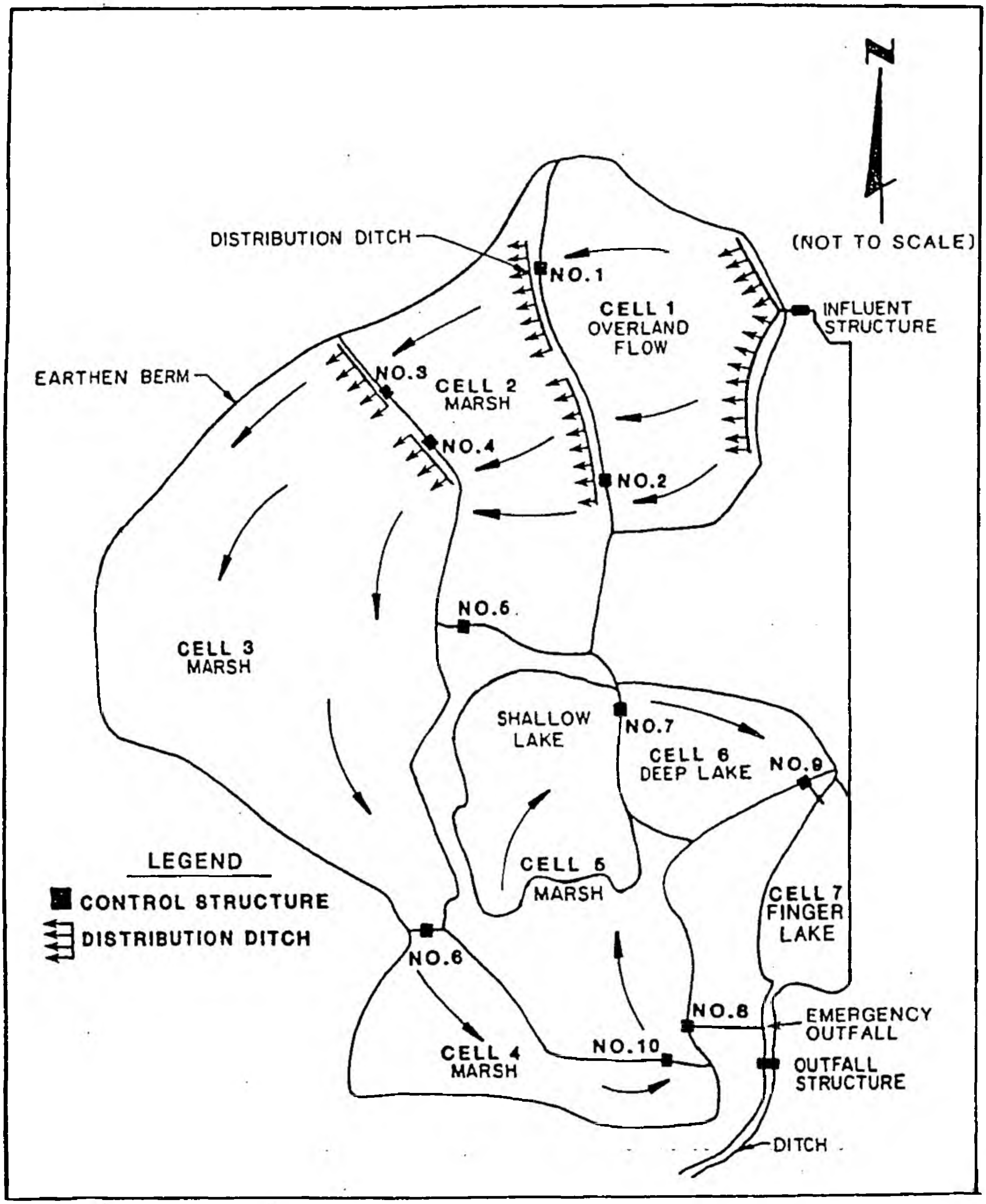
Part of the distribution system to one of the early cells was built on an area of phosphate mine slimes. An early collapse has resulted in inadequate flow control, leading to preferential flow routes developing across the receiving cell.

Inflow quality has been better than expected for BOD and suspended solids, and effluent quality was originally considerably better than the limits. Recently, the wetland has been effective at removing nitrogen and phosphorous, mostly by the end of the second cell. It has not been so efficient for BOD and suspended solids removal, primarily due to algal blooms which have occurred in the lakes. Faecal coliform counts on the effluent may be three times higher than on the influent water.

2.2.5 Additional Benefits

The wetlands are extremely attractive to wildlife, particulary birds.

Figure 3. Lakeland artificial wetland system flow distribution and control structure layout.



2.2.6 Costs

Total capital cost were \$8.8 million (about £5.2 million) of which wetlands costs were \$3.2 million (about £1.9 million). Grants of \$4.2 million (about £2.5 million) are expected. Information on operating costs is not available.

2.2.7 Summary

The system is operating at considerably less than design capacity. It is reasonably successful. Some of the problems are due to poor design - having large areas of open water near the end of the system - and some are due to poor operation and maintenance - the lack of repair of the collapsed delivery channel. The additional benefit of the attractiveness to wildlife is not utilised as a tourist resource. Whilst the site had some interesting positive features, the visit was most useful for the identification of problems which can occur in wetland development.

2.3 Pennsylvania Coal Region

2.3.1 Introduction

Within the Pennsylvania Coal Region three mine and related acid drainage remediation schemes were visited. Whilst observations of parts of sites were restricted by snow cover, the presence on-site of Doug Kepler and Eric McCleary (of Damariscotta, a wetland design company) provided a considerable bonus.

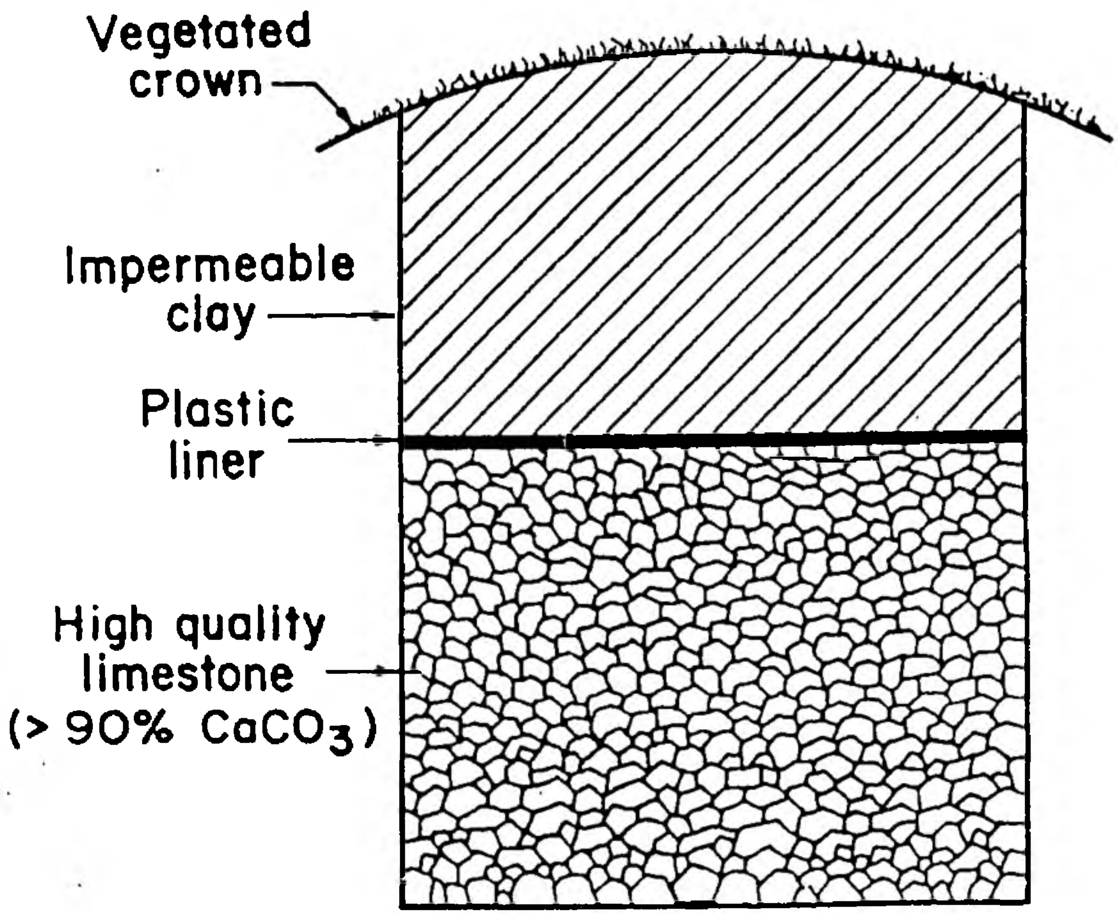
The sites visited were as follows: Howe Bridge, R.E.M., and Morrison sites. Each site utilized anoxic limestone drains, followed by wetland treatment to provide treatment of acid mine drainage emanating from abandoned coal workings. Site visits were guided by Bob Nairn of the US Bureau of Mines.

The method of funding and construction of the Howe Bridge scheme is of interest in that local and national organizations cooperated to produce a low costs local community solution to an environmental problem. This approach is being attempted for further acid mine drainage sources, draining to the Mill Creek. Details of contributing organizations are given within Arthur D. Little report No. 40922. The report also details the technical principles and design features of the schemes. General features are given below.

2.3.2 Systems Design

The systems exhibit a common layout comprising anoxic limestone drains followed by oxidation ditch, passive oxidation/settlement ponds and finally wetland treatment. In each case the anoxic limestone drains were formed from limestone with a $CaCo_3$ content of greater than 90%. The drains were sealed using polythene and clay cover to inhibit oxygen infiltration. (See Figure 4.)

Figure 4. General cross-section of an anoxic limestone drain.



Downstream of the anoxic limestone drains, passive oxidation/ settlement of metals was provided. At Howe Bridge, a ditch ran from the anoxic limestone drain to the settling pond. Within this ditch considerable quantities of presumably oxyhydroxide sludge had accumulated. Such observations led to development of ideas by the project team relating to the enhancement of oxidation by cascades and continuous cleaning systems.

From the oxidation/sedimentation ditch mine water was fed through anaerobic/aerobic wetland systems. From discussion with Doug Kepler and Eric McCleary, it is apparent that the wetlands design is currently subject to progressive refinement with construction techniques focusing upon elements considered to be critical to system operation. By way of example, early wetland construction paid particular attention to planting layout. However, over time a more relaxed approach (such as throwing plants in!) has produced equally satisfactory vegetation cover.

As a counter to this relaxation of certain aspects of construction, the control of flow through the wetland system is receiving close attention. Kepler and McCleary and the Bureau of Mines advocate an aerobic/ anaerobic approach to wetlands design, which models natural wetlands. Earlier constructed wetlands utilized top feed/bottom discharge flow systems and currently developed sites (e.g. R.E.M.) are being constructed with cells designed to optimize anaerobic bacterial processes which precipitate metal sulphides.

The preferred substrate utilized on site was mushroom compost. This organic rich material also contains limestone which adds alkalinity to water within the wetland, essential to the buffering of acidity generated by the deposition of iron in oxidized conditions.

2.3.3 Constraints

Experience gained by the US Bureau of Mines has identified a number of constraints upon the effective utilization of anoxic limestone ditches. It is suggested that drains should not be constructed for water with Eh >+300mV, pH >6 or DO >2mg/l. The presence of ferric iron and high concentration of aluminium and sulphate can potentially give rise to armouring of limestone and possible clogging difficulties. These factors underscore the earlier project team recommendation, that complete raw mine water quality data should be collated for Wheal Jane. Knowledge of flow conditions are also vital to the design of the drain, precipitation ponds and wetlands.

The area available for wetland construction is clearly a major constraint, although treatment capacity can be enhance by optimization of anaerobic zones within the wetland.

2.3.4 Performance

Performance criteria are documented for Morrison only.

At Morrison mean mine water acidity was recorded as 446 mg/l with trace levels of alkalinity. After flowing through the drain mean alkalinity of 262 mg/l was recorded. This is equivalent to generation of an average of

74 grams of alkalinity per day per cubic metre of water. pH increases from a mean of 4.7 to never less than 6.0. Total iron, sulphate and manganese were unaffected. Slight problems of precipitation within the drain were controlled by flow control to ensure no air entry into the drain. Overall, the system functions well with final effluent pH >6 and iron <2 mg/l. Manganese is discharged at a concentration of >10 mg/l, however, this does not affect compliance.

2.3.5 Benefits

The systems have been shown to be capable of replacing previous chemical treatment systems. Wild fowl have been attracted to the wetland systems by the provision of nest boxes. The systems have been demonstrated to be capable of treating small flows associated with abandoned coal workings.

2.3.6 Costs

The Howe Bridge wetland treatment system was constructed using community help for approximately £25,000. The Bureau of Mines have estimated the equivalent construction costs using conventional methods to be of the order of £60,000. The system has a flow rate of less than 200l/ minute (i.e. less than 3% of current Wheal Jane flow rate). Costing details for Morrison and REM, are not available.

2.4 American Crystal Sugar Company's Wetland, Hillsboro, North Dakota

2.4.1 Introduction

The sugar refinery at Hillsboro produces 300,000 gallons of wastewater each day during a 185 day processing season. The existing treatment facility cannot achieve the discharge consent conditions, and the company had to store the water until a more suitable treatment method was found. The chance reading of an article in the magazine "Ducks Unlimited" led to the recent construction of an artificial wetland. Work began in 1989 and should be completed during 1992. The wetland will provide tertiary treatment to the existing aeration and settlement plant. Pete Anderson (Factory Chemist) accompanied us on a tour of the wetlands.

2.4.2 System Design

The wetlands will occupy 129 acres on a 160 acre site. Figure 5 shows a plan of the site. Rectangular cells have been created by the construction of earth berms, the borrow pits becoming the cells. Water is delivered through simple concrete structures at 10 foot intervals, feeding perforated plastic pipes. Cells 1, 3 and 5 are narrow and shallow. Cells 2, 4, 6 and 7 are wider with a deeper central section, in which islands have been constructed specifically as wildfowl nesting sites. Cell 8 is a large, deep storage unit, and cell 9 is a final polishing wet meadow. Small parts of the earlier cells were planted mainly with cattails (Typha latifolia) and bulrushes (Scirpus spp). Natural invasion is expected to fill the remaining areas. Inflow quality varies between 25 - 75 mg/l BOD in summer, to 150 - 200 mg/l BOD at other times.

2.4.3 Constraints

The land in this part of North Dakota is extremely flat, and there is only a 6" difference between pond levels. The northern latitude means that the system is frozen and hence inoperable for several months each year. Large storage reservoirs are necessary to overcome this problem.

2.4.4 Performance

Ice has damaged some of the plastic delivery pipes. Many plant species did not establish themselves, probably due to inefficient depth control at the critical time. Water retention time is about 14 days. There is a considerable improvement in quality across the first cell, with the BOD reducing to about 25 mg/l, and dissolved oxygen concentrations increasing from zero to 10 mg/l.

2.4.5 Additional Benefits

The site is attractive to birds. Waders had moved in within six weeks of planting, and overall about 40 species have been observed. This aspect is enjoyed by some of the factory staff. The success, so far, of this project has led the company to consider building similar wetlands at some of its other refineries.

2.4.6 Costs

The capital cost is expected to be about $1.7 million (£1 million) which compares favourably with $5 million (£3 million) for an "active" treatment system. Annual operation and maintenance is expected to be equivalent to 0.5 man/year.

2.4.7 Summary

The completed part of the system appears to be working well. Valuable experience has been gained in planting techniques and the control of plant establishment. The flow delivery system will not be appropriate for use in a Carnon Valley wetland, and the design of the wetland cells is similarly inappropriate.

2.5 City of Minot, North Dakota, Wastewater Treatment Facility

2.5.1 Introduction

Minot's population and industrial growth resulted in the city's sewage treatment works being hydraulically and organically overloaded. Although expansion of the works in 1983 gave increased storage and discharge consent compliance, there were more public complaints about odours. A reassessment of the whole sewage system led to many changes, including the construction of a wetland to remove excess ammonia before discharge to the Souris River. Mr. George Christensen (Mayor) and Mr. Lyle Weeks (Chief Engineer) accompanied us on a tour of the wetlands.

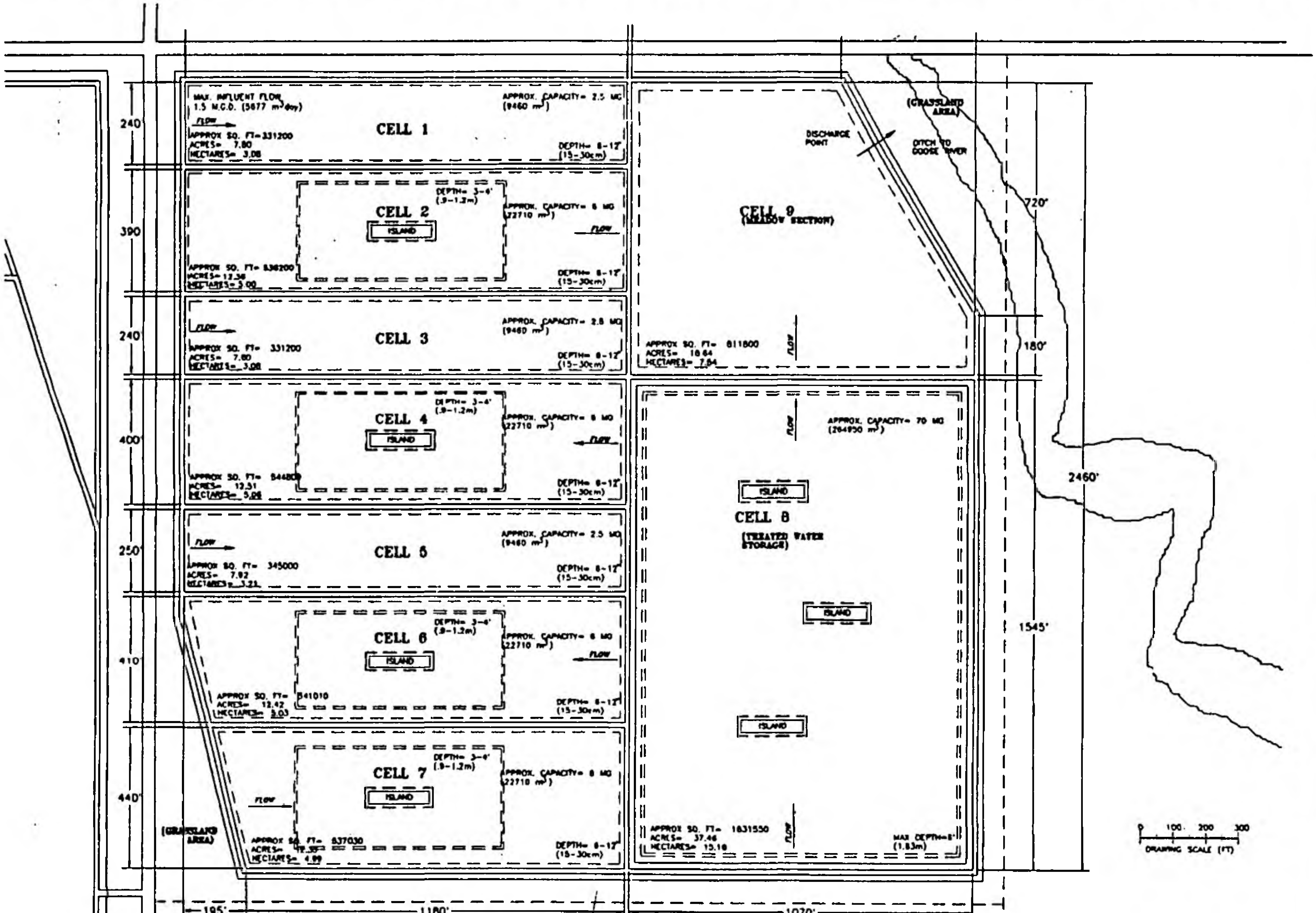


Figure 5. AMERICAN CRYSTAL SUGAR HILLSBORO, NORTH DAKOTA WETLAND LAYOUT

2.5.2 System Design

The wetlands consist of four parallel cells, each of 31.1 acres. Figure 6 shows a plan of the system. Each cell has five zones of varying water depth, planted with different vegetation communities. The design flow is 7.5 mgd from either of two sources. The inlet control structure has butterfly valves and should have flow recorders. Reducing plastic piping with valves and upstanders feed the water to each cell, which allows individual cells to be taken out of commission for periodic maintenance. Flow from cell to cell is controlled by simple weir structures.

2.5.3 Constraints

The land is extremely flat and there is little difference in head across the system. To ensure optimum flow through each cell, a complex system of valve operation is necessary. Occasional vegetation control may be required to maintain the hydraulic profile.

The northerly latitude means that the wetland can operate for only five months each year. During winter, the distribution system has to be drained to prevent ice damage.

The monitoring of mosquito populations will be essential so that controls can be exerted and nuisance be limited.

2.5.4 Performance

The system is newly built and there are insufficient data to assess performance. Flow monitoring is not to design standards.

2.5.5 Additional Benefits

Some cells have islands specifically to attract wildfowl.

2.5.6 Costs

No information is available. O & M costs are expected to be higher than for other sites visited, due to the onerous valve operations.

2.5.7 Summary

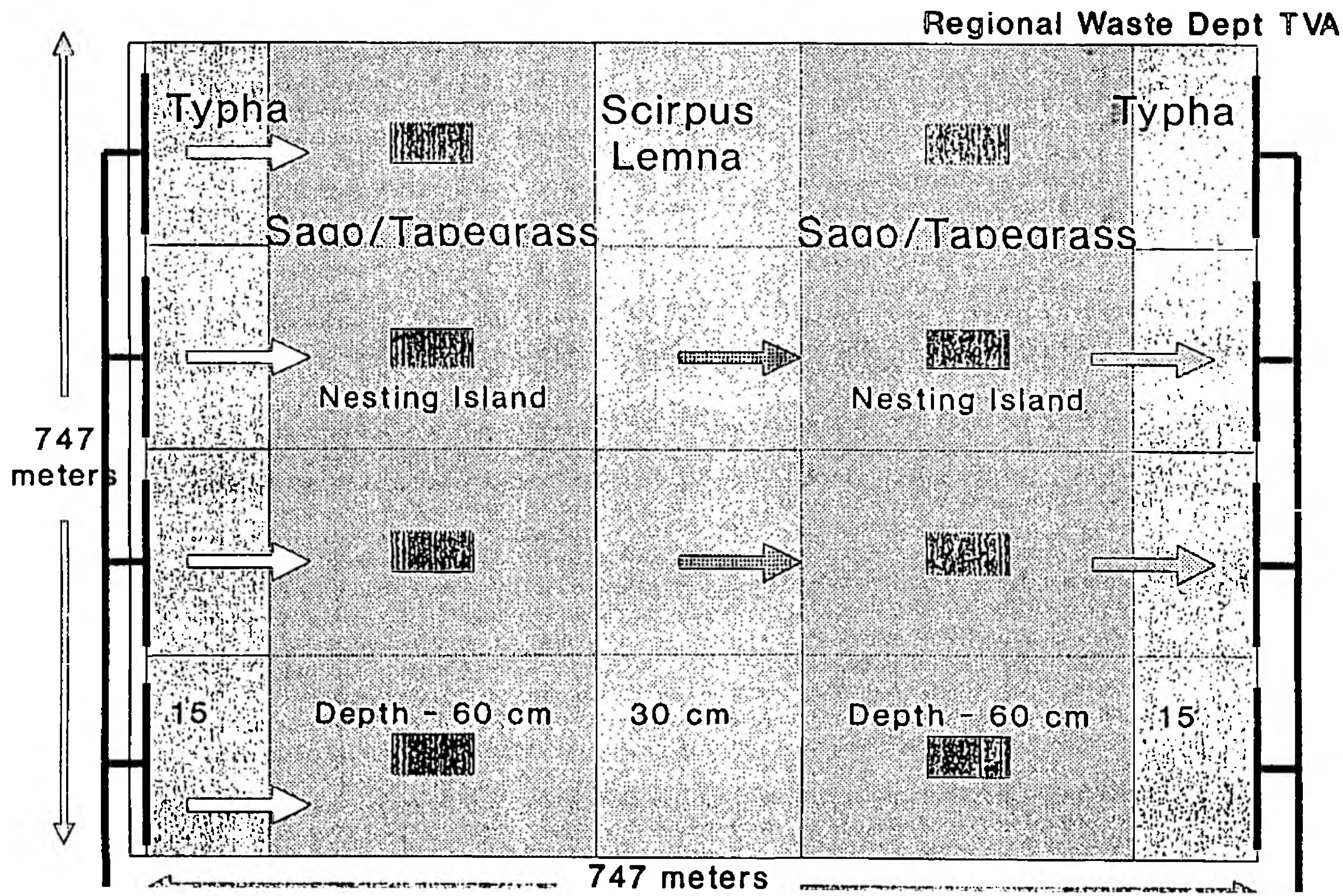
The delivery system and final outfall structure appeared to be over-designed and not operating effectively. Flow monitoring is haphazard despite the detailed planning. A quality monitoring programme is being planned. Inadequate emphasis on these aspects will make efficient management of the system difficult to achieve.

2.6 Colorado School of Mines and the "Big 5" Tunnel Research Project

2.6.1 Introduction

Prior to our visit to the "Big 5" tunnel project and the Central City Mining District, Ron Cohen of the Colorado School of Mines gave a short presentation. During the talk he touched on historical development of the scheme, areas of technical interest, and the potential requirement

Figure 6. MINOT WETLANDS SYSTEM



for further research. The presentation was given from the perspective of an advocate of anaerobic sulphate reducing bacteria systems, although tolerant of alternative ideas.

The potential mechanisms for metals removal include plant uptake, filtering absorption, etc. However, Ron Cohen's research has demonstrated that the primary removal can be attributed to sulphate reducing bacteria. Subsequent research within the school has sought to gain an understanding of the mechanisms, to develop substrate conditions suited to sulphate reducing bacteria, and to control flow through the substrate.

Following a site inspection at the "Big 5" tunnel project at Idaho Springs and a tour of the Central City Mining Project, member of the research team provided details of on-going research which were stimulating and contributed to the final recommendations set out in ADL Report No. 40922.

2.6.2 System Design

The "Big 5" tunnel project is an EPA funded research site, investigating the potential for biological treatment of metal contaminated acid mine drainage. The research facility is small, comprising a number of dustbin and small pilot scale test cells. The project has received very close attention and a large number of research papers have been published, dealing with substrate selection, flow control, substrate permeability, metal removal rates and microbiology.

The details of the anaerobic bioreactor studies are given in previous consultants' reports, together with the basic chemical and microbiological function of sulphate reduction.

The principal substrate used after apparently extensive laboratory bench scale experimentation is aged cow manure and barley mash. The function of the substrate is to provide a location for colonization and nourishment for bacterial populations. By careful observation it was noted that hay (or water extracts of hay) significantly increased the sulphide generation rate within the test cells. This mechanism is not fully understood, but may be attributed to a number of factors such as provision of simple form carbon food source for the complex microbial community. Hay is now mixed into the substrate to improve metal removal rates.

Various flow regimes through the test cells were tried. Horizontal flow was found to be prone to rapid clogging (see Figure 7). Vertical downward flow was subject to short circuiting and required precise control, (see Figure 8) whilst vertical upward was found to be the most manageable.

2.6.3 Constraints

The project appeared to be constrained by budget and appeared a little "Heath Robinson" in construction. However, the amount of research data generated from the scheme is impressive. Construction materials were clearly selected on the basis of cost and hence the performance of certain parts of the system were found to fall short of expectations.

Figure 7. "Big 5" Cut-a-way view showing horizontal Flow Control.

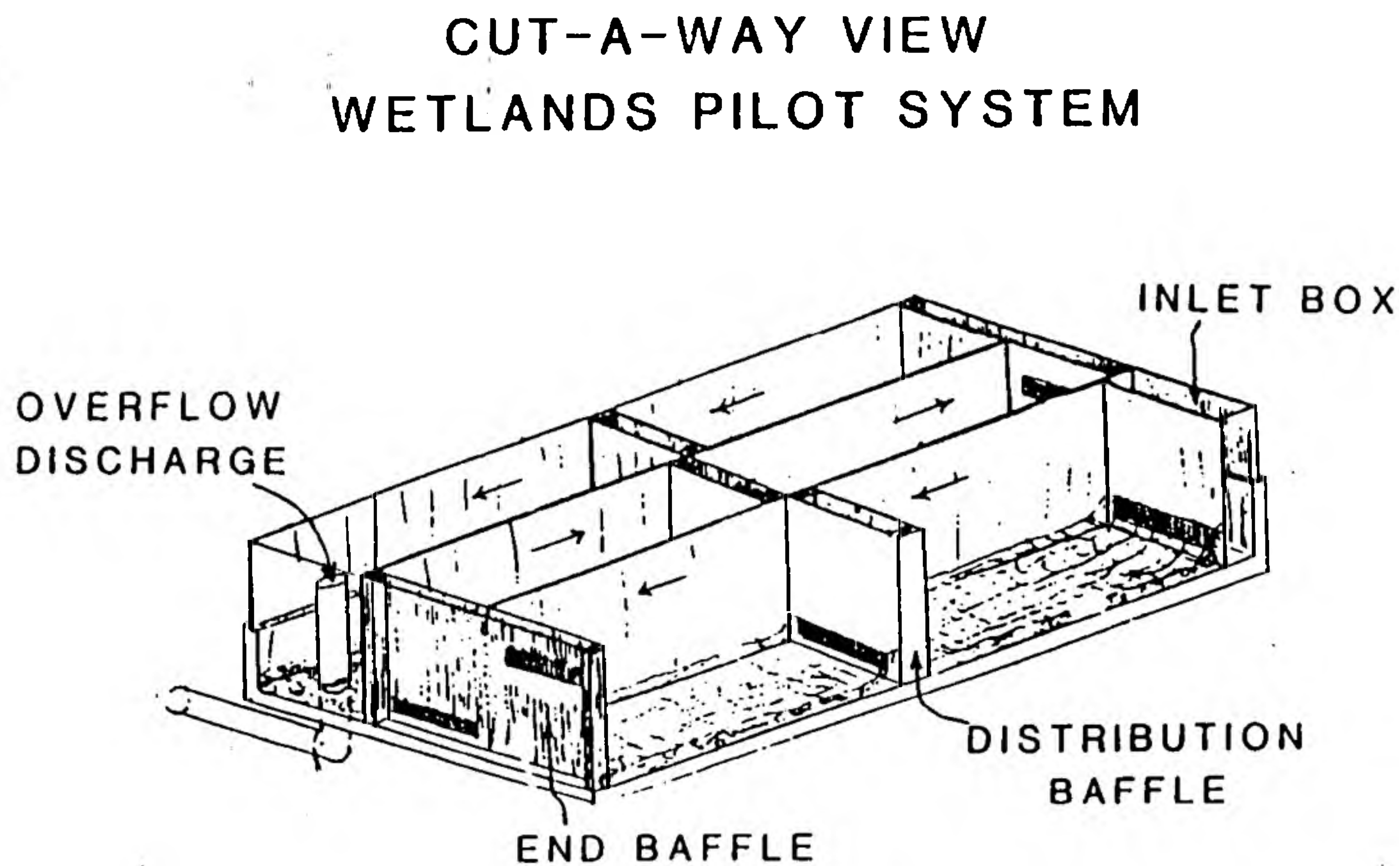
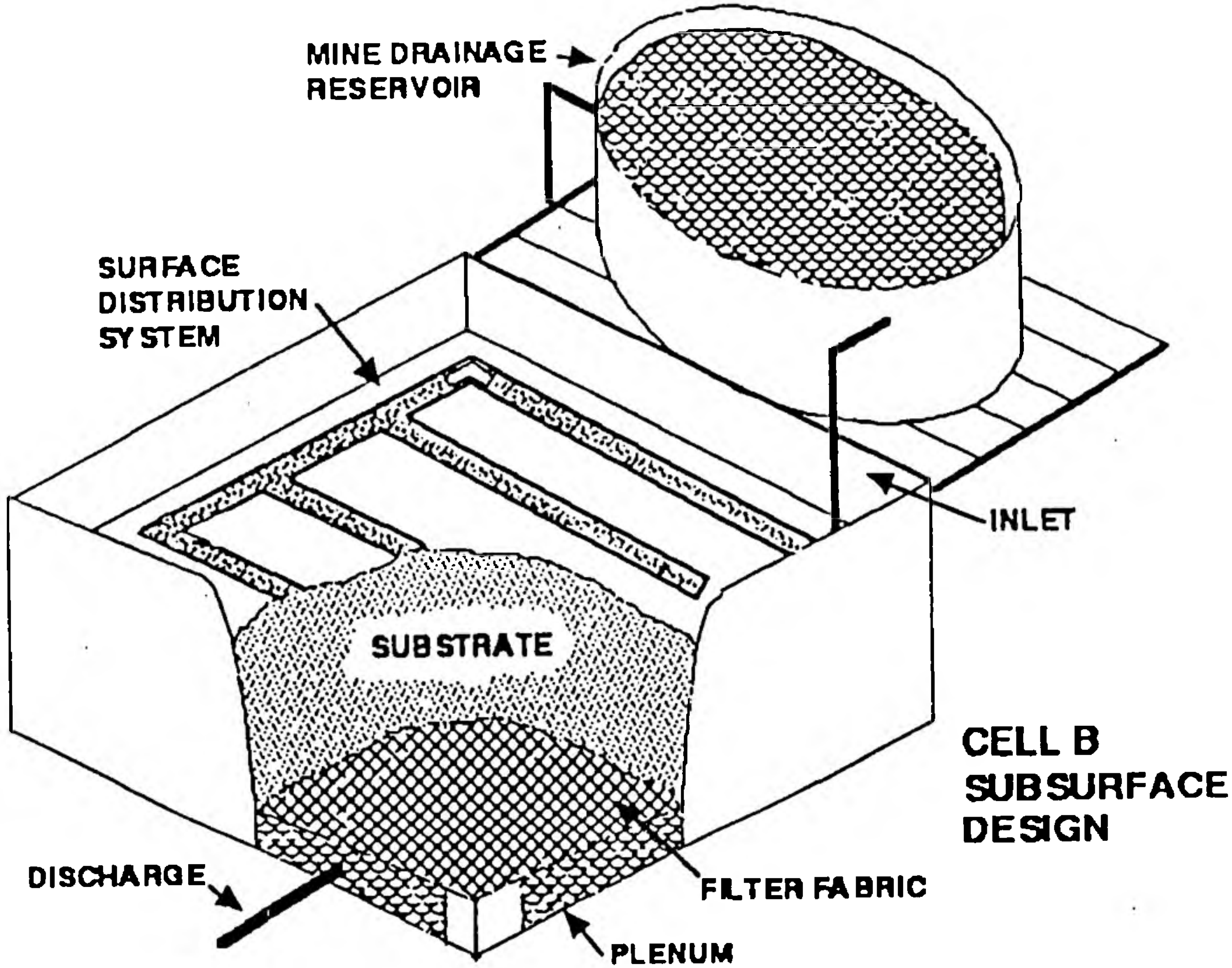


Figure 8. "Big 5" Cut-a-way view showing vertical Flow Control.



The primary constraint of the anaerobic bioreactor approach is their ability to handle flow. The "Big 5" system has treated maximum flow volumes of 4 l/m.

Clogging of associated pipework was noted as an operational problem, although it was considered by research workers that upon scaling up and by the careful selection of valves etc. these problems could be overcome.

2.6.4 Performance

The research project comprises three cells containing different substrates:

Cell A	Mushroom compost (30% around manure, 50% barley mash)
Cell B	Equal parts manure, peat, wood shavings
Cell C	As Cell B with 15 cm limestone at base

All cells were prone to some seasonal decreases in performance due to low winter temperature.

Cell A was the most effective and supported the highest population densities of algae and bacteria. Reported metal concentration decreases range from 0 to 54% for Al, 0 to 21% for Mn, 0 to 96% for Ca, 9 to 63% for Fe and 7 to 100% for Zn.

2.6.5 Benefits

The potential benefits of the system include the precipitation of a dense sulphide precipitate captured with the organic substrate mass. Some potential exists to the use of such metal rich organic wastes by smelters. Anaerobic bioreactors are still at the research stage and, low flow rates probably preclude their inclusion within the Carnon valley restoration scheme.

2.7 Meeting with Knight Piésold - Denver

2.7.1 Introduction

Preliminary informal discussions were held with John Gormley and Lorraine Fillipek of Knight Piésold and Co., Denver, Colorado. The purpose of the discussions was to review the nature of the Wheal Jane mine water remediation scheme with another consultancy group with experience within the field. It was hoped that supplementary experience of passive treatment systems could be gained. The requirement for detailed design capability for the implementation of the final Carnon Valley Scheme has been identified and the meeting provided an opportunity to review the resources of the company.

2.7.2 Scope of Discussions

John Gormley, Vice President of Knight Piésold Management Corporation, outlined the company's general qualifications, background and experiences with passive treatment systems, including constructed wetlands, soil disposal systems and other land applications. Following a general review of the flow and water quality conditions currently monitored at Wheal Jane, more detailed discussion of specific aspects of the project and potential areas of previous experience ensued.

The potential for geochemical modelling of the system and the prediction of the future mine water quality were discussed. Lorraine Fillipek has specific expertise within this technical field. After consideration of the complex history, mineralization, geometry and flow paths of the Wheal Jane and associated workings, Lorraine Fillipek endorsed the project team's supposition that geochemical predictive modelling is not a viable objective.

Lorraine Fillipek also lent support to the reported experience of increased metal concentration in drainage following recent recharge, and concurred with the team's view that this may be due to re-wetting of exposed oxidized minerals.

John Gormley outlined Knight Piésold's worldwide experience of design and inspection of tailings dams and leach piles. Photographic records of such projects prompted discussion of principles and tailings dam design and, in particular, of the relative merits of sub-aerial and subaqueous deposition. A major objective of tailings dam operation is the minimization of the pond area within the dam to optimize the formation of drained dense deposits - a factor of key importance to the Wheal Jane tailings dam, discussed further in Knight Piésold Report Number 1820A/R7027/RHC.

A presentation of Knight Piésold's contribution to the "Big 5" mine drainage research project was given by John Gormley. It is understood that Tom Wildeman of the Colorado School of mines is retained by Knight Piésold. From the presentation it was understood that Knight Piésold's contribution was in the area of flow control through the anaerobic wetland research cells. The merit of upflow was reinforced on the basis of field experience. It was a little disconcerting to hear the implied Knight Piésold ownership of the project having previously discussed the project with Colorado School of Mines, the developers of the research project.

The project team was given a tour of Knight Piésold's facilities and particularly the CAD Section. Such design facilities are widely available within the UK.

2.7.3 Summary

1) Predictive modelling of the likely mine water quality was considered to be impractical.

2) The experience of increased metal concentrations within mine drainage following recent recharge was reported.

3) Knight Piésold have undoubted worldwide experience with tailings dam design and inspection, although, in common with most companies, have little direct experience of passive mine water remediation.

2.8 Meeting with the Environmental Protection Agency, Denver, Colorado

2.8.1 Introduction

The US Environmental Protection Agency (EPA) is a federal organisation with the responsibility for enforcing environmental legislation. It operates through ten regional offices. That in Denver covers the states of Colorado, Montana, North Dakota, South Dakota, Utah and Wyoming. A meeting was held to discuss the regulation of acid mine drainage and the resolution of pollution problems through "Superfund". EPA officials attending were Ms. Holly Fliniau (Chemical Engineer), Mr. James Hanley (Project Officer), Mrs. Carol Russell, Ms. Dana Allen and Mr. Jack White. Mr. Stephen Sterling of the Morrison Knudsen Corporation attended part of the meeting to discuss one aspect of the Superfund programme.

2.8.2 Legislative Framework

Air and water pollution control, and matters relating to radiation and toxic substances are dealt with under the Clean Water Act 1970. The sections on water pollution cover standards, surface, groundwater and drinking water compliance, wetlands protection, non-point sources, and construction grants. Hazardous wastes are dealt with under the Resource, Conservation and Recovery Act 1976 (RCRA), and the Comprehensive Environmental Response, Compensation and Liability Act 1980 (CERCLA), generally known as "Superfund".

The control of mine waste is not clearly defined to any of these Acts. The areas of responsibility are often blurred. The mining industry has a strong lobby in Congress, and some of its activities tend not to be included in the controlling legislation. An attempt is being made to have mine waste controlled under the RCRA. A consultation document is with Congress, which has restricted its progress. It is unlikely that this will be resolved during 1992.

2.8.3 Superfund

Under Superfund, the EPA has powers to act in emergencies, to fund remedial works, and subsequently to recover costs. A long, involved and costly process of assessment is undertaken before remedial works are funded and implemented. The steps are:

* Site discovery and investigation, usually by State officials.

* EPA evaluation of possible hazards, using a somewhat subjective points rating system, and a decision on whether or not to include in the National Priority List (NPL). Some of the difficulties associated with this stage are the barring of certain waters from the NPL, anomalies which result in obvious problems achieving low scores, the ability of some companies to block progress, and until recently the lack of emphasis on environmental impact.

* Negotiations to encourage potentially responsible parties to pay for remediation.

* Detailed studies and feasibility assessment. This identifies what contaminants are present, how serious the problem is, the potential risks to the community, and the most effective remediation methods. The option of no action is always considered. It is expected that 18 to 30 months are required for this step, but some sites are still at this stage after 12 years. The average cost is about $1 million (£600K).

* Publication of the EPA's proposed remediation plan, followed by public consultation, and selection of the method to be used. The proposal must protect human health and the environment; appropriate standards must be achievable; it must be cost-effective; and innovative technology should be used. There is a conflict between cost-effectiveness and the use of innovative technology and, as a result, the EPA tends to rely on standard, proven technology.

* Detailed design of the method to be used. This takes 12 to 18 months and costs, on average, $1 million.

* Actual clean up, by the responsible party or a hired contractor. The EPA has powers to recover costs and three times full damages. This stage takes one to six years for surface waters, and could take much longer for groundwaters.

The private view of some EPA Officers was that present owner liability is unfair. If no responsible party is found, a contract may be let to the State, which may be sued if things go wrong. Such an action is presently being considered. Individuals can sue violators under the Clean Water Act 1970, but connections between this and Superfund liability are unclear. An area of the law which is being developed is that of indemnity.

Summaries of Superfund programmes at two sites were given by James Hanley and Stephen Sterling.

The Superfund obtains its money from a levy on the chemical and petroleum industries (75%) and a general tax (25%). The fund is now $8.5 billion (£5,000M). The National Priorities Lists contains about 1,200 sites, of which about 2% are related to mining. Work is progressing at over 1,000 sites and actual clean up has started at almost 500.

2.8.4 Overview

The legislation is complex and confused. It was suggested that economic and political pressures are being exerted to prevent improved legislation being introduced, and to limit the effectiveness of existing Acts. A vast effort has been made in creating a system which has enormous problems. These are principally in the priority rating of real environmental problems, the delay in dealing with them, and the high costs incurred.

Some of the projects which have achieved NPL status are small in comparison with many of the problems undertaken by NRA regions, and tiny when compared with Wheal Jane.

The EPA is clearly a super-bureaucracy, with all the negative as well as positive implications of that word. There was considerable agreement on many issues, perhaps not surprising in a meeting between regulators. It was recognised that both UK and US systems had good points and bad. The contacts made with the EPA are considered to be extremely useful, not only in respect of mining problems, but also in relation to separate discussions on agricultural pollution control.

3.0 LESSONS LEARNT BY SUBJECT

3.1 Dealing with High Flows

Three of the sites were on relatively flat land (Orlando, Hillsboro and Minot) and this created problems with maintaining the hydraulic gradient. Control structures which worked best were of simple design and construction. The problem of flat land led some of the designers into more complex structures which required a greater degree of operational effort. The best approach seems to be to carry out a detailed topographic survey to enable accurate weir levels to be calculated, and to use simple passive structures.

Extremely variable flows (Orlando and Lakeland) need a delivery system of substantial construction. The concept used at Lakeland was the best, but the collapse of part of this structure emphasizes the need for a detailed substrate quality survey before planning and construction.

All sites had the objective of sheet surface flow. This was not being realised for a number of reasons, although that most likely to succeed was the passive delivery system at Lakeland, which had numerous openings between the ditch and the receiving cell. Some degree of vegetation control is necessary to maintain sheet flow. On flat sites, this will also assist with maintaining the hydraulic gradient. Surface flow is not necessarily the most appropriate for dealing with acid metal rich water.

The harsh environmental condition of prolonged freezing will be experienced regularly at two sites (Hillsboro and Minot). It is unlikely to be a major problem in the Carnon Valley but a single incident could have a significant effect. Design and choice of materials for the delivery system need to take this into account. Neither of the sites in North Dakota was perfect in this respect. The solution at Minot, of draining the delivery system in autumn and the complex re-start procedure in spring, is time-consuming.

Depth control, which is necessary to facilitate the establishment of aquatic vegetation and during storm surge flows, inevitably requires much operational effort. A simple weir board design is probably the most effective although, for storm flows, a large system with large individual cells gives a greater buffering capacity. Orlando and Lakeland were effective at buffering storm flows for this reason. Depth control to improve plant establishment can also be achieved by constructing the cells with varying substrate levels. This had worked well at Orlando and had also been taken into account at Hillsboro and Minot.

Flow monitoring throughout a complex system seems to be a sensible approach, so that individual cell effectiveness can be assessed and, if necessary, remedial action taken. This was well understood at Lakeland, although it is possible that some flow data are calculated rather than measured.

All these controls can be negated by the activities of burrowing animals. Whilst muskrats and beavers are not expected in the Carnon Valley, rabbits could cause problems. Berms will need to be protected.

3.2 Dealing with Acidity

The processes of oxidation of exposed metal sulphides (principally pyrites) and subsequent saturation of deposits when dewatering of mines is discontinued generally generates acidic drainage. The process is bacterially catalyzed and its onset is rapid and generally remains a long standing environmental problem. The acidic nature of mine drainage also results in the dissolution of metals which can have significant impact upon receiving water courses.

To reduce metal content and minimize environmental impact and to achieve statutory water quality objectives or compliance standards it is necessary to control the acidity of emergent mine waters. Traditionally, where attention was paid to this problem, conventional lime dosing, oxidation, and precipitation of hydroxide sludge was utilized. However, where acidity is high with attendant high metal concentrations, lime dosing costs can be substantial and unacceptable, following the closure of mines.

New mines developments in many countries are required to have a financially backed mine closure plan, dealing with drainage, tailing dams and leach piles, etc. However, poor attention to these aspects and the current legal loophole referred to in section 3.4 have resulted in many locations, where long term acid drainage is an actual or foreseen environmental problem. Hence the need for effective acidity controls are required.

The emphasis of this study tour was to examine schemes for dealing with historical problems where adequate mine closure plans had not been prepared or adhered to and therefore analogous to the UK situation. It should be noted that, with careful pre-planning of mine closure, acid mine drainage generation can be reduced significantly.

Natural wetland systems and anaerobic bioreactors have been shown to be capable of buffering acidity within mine drainage. Modified artificial substrates such as aged manure and mushroom compost are seen to buffer acidity. Manure typically has a pH of 8.9, whilst the carbonate content of mushroom composts is able to add alkalinity to mine drainage.

From observations in Pennsylvania and documented cases elsewhere within the United States, pre-control of acidity and increased alkalinity prior to wetland treatment enhances overall system performance and discharge compliance.

Pre-treatment is effected by use of anoxic limestone drains. For example, at Howe Bridge pH was raised from 3.07 to 4.95 and 150 mg/l of alkalinity were added by the anoxic limestone drain.

A number of key lessons were learnt during the US visit, namely:

i) The importance of fully characterizing mine water drainage and flow prior to the construction of drains.

ii) Attention to carbonate source quality (>90% $CaCo_3$) and grading (large 2 - 4 cm stone of single size) result in higher carbonate dissolution rate and minimization of clogging problems.

iii) Awareness of potential for precipitate clogging the drain. Potential precipitates include aluminium and ferric oxyhydroxides, zinc and copper oxides and hydroxides, and gypsum. Such precipitates could reduce hydraulic and chemical performance of the drain by clogging or armouring of stone.

iv) Importance of sealing of the drain to reduce oxygen infiltration and to enhance carbon dioxide partial pressure.

v) Careful hydraulic control to ensure elimination of oxygen.

3.3 Dealing with Metals

The quality of emergent acid mine drainage is controlled by the geochemistry of the ore body. In a complex system such as the Wheal Jane and related mine workings, this results in variations in mine water quality through the system. The characterization and distribution of mine water quality will be an important factor in the pre-remedial construction works monitoring.

Observations in the US suggest that mine water chemistry within the Wheal Jane mine is unusual and is not matched by similar levels of metal concentrations. Notwithstanding this, it is the general view of US contacts that with adaption available passive treatment technologies would offer a major input to the solution of the problem. The magnitude of the Wheal Jane and associated Carnon valley mine water drainage legacy will require the development and extension of current state of the art technology. Furthermore, no single technology will be capable of providing a satisfactory solution to the problem.

The main mechanism of metals removal observed are as follows:

i) pH adjustment followed by oxidation and precipitation of oxyhydroxides.

ii) Precipitation of sulphides within anaerobic bioreactors and anaerobic zones of wetlands.

The potential exists for the precipitation of metal sulphates or carbonates, however, considerable research and feasibility assessment is required to enable the viability of such technology to be evaluated.

As stated, metal loadings observed in the US, where passive systems have been implemented, are substantially lower than in the Carnon valley. Consequently, the issue of metal rich precipitate management is less pressing. However, where pH regulation, oxidation and precipitation are utilized, large volumes of low density sludge are being generated. Typical management includes for back-hoe excavation of sludge from the oxidation ponds with transport to landfill.

The metal loadings within mine water from Wheal Jane will place the management of the resultant metal rich wastes on the critical path in the development of a Carnon valley remediation scheme.

The alternative strategy adopted and observed within the US is to precipitate metal sulphides. Such precipitates are considerably denser than for example hydroxides. However, such acid volatile sulphides are liable to re-oxidation with liberation of metal and generation of acidity. Hence such waste generation is undesirable.

Anaerobic bioreactors which seek to enhance conditions for sulphate reducing bacteria, are currently operated at very small scale and low flow rates, rendering such technology unlikely to be capable of scale-up within a reasonable time period. The aspects of substrate engineering observed should be incorporated within the proposed tertiary wetland.

Currently, work is required to assess the likely input and output parameters of an integrated treatment system within the Carnon Valley. It is envisaged that a secondary (active) stage treatment will be required to treat anoxic limestone drain effluent to sufficiently low metal concentrations for input into the tertiary treatment wetland. Details of such recommendations are contained in Arthur D. Little report No. 40922.

4.0 IMPLICATIONS FOR THE UK

4.1 Implications for Wheal Jane

A comprehensive report has been prepared by ADL/MHE which documents the details of sites visited and set out a strategy for the implementation of a long term solution to the Carnon valley mine water drainage legacy. One of the principal findings of the report is that no single method of passive treatment is sufficiently advanced as to offer a solution. However, by integration of several of the systems observed with the US, it is considered that a treatment process can be developed.

The combination of anoxic limestone drains and wetlands was observed in the Pennsylvanian coal mining region. However, current metal loading within the Carnon valley mine drainage is considerably greater than observed in the US and it is not considered feasible to utilize such a simple system.

The development of a three-stage integrated system is a logical extension of historical development of passive treatment technology. Existing technologies will require preliminary investigation to ensure that the chemical and physical conditions are suitable for the development of the systems. Preliminary results are, however, encouraging. Using a pilot, then full scale construction approach will allow for the required refinement of systems to be undertaken to match treatment to mine water quality and discharge objectives.

The study of US coal mining draining remediation of Mill Creek presents a further model approach analogous to the Carnon valley. It is recognized that the Carnon cannot achieve its environmental quality standard without treatment of the Wheal Jane discharge and the County Adit discharge. Similarly, in the Mill Creek region, each mine water discharge is being treated individually with a progressive improvement to the river's quality. Whilst the Mill Creek can be tackled by a number of small scale schemes often utilizing community involvement, the magnitude of the Carnon valley pollution will require large scale political and financial commitment.

4.2 Implications for UK Coal Mining Areas

The legacy of abandoned coal mines with attendant acid mine drainage observed in Pennsylvania bears marked similarity to the situation in the UK. Systems developed by the US Bureau of Mines including anoxic limestone drains and vegetated aerobic/anaerobic wetlands appear to offer an excellent opportunity to tackle acid mine drainage using passive treatment with low long term operations cost.

Polluted mine water from formerly worked pyritic coal seems is a major environmental problem within for example the South Wales Coalfield. The most obvious impact of acidic and ferruginous mine waters is visual yellow orange discolouration of watercourses. However, the impact upon aquatic communities is a serious consequence. In South Wales alone it is estimated that over 50 km of rivers and streams including at least 30 km of classified water are affected. Perhaps the greatest impact of mine water pollution is felt in the smaller streams which are not classified under the river quality assessment scheme. Such streams are often breading grounds and sites for development for juvenile fish.

The problem of acid mine drainage in the UK is likely to continue to grow as further mines are abandoned. It is essential that a legal framework for the control and remediation of mine waters is developed. In parallel, technologies should be developed that are capable of providing a low cost method of mine water treatment. It is considered that the combination of anoxic limestone drains with vegetated aerobic/anaerobic wetlands offers and extremely good opportunity to develop such treatment techniques.

4.3 Implications for Sewage, Industrial and Farm Effluent Treatment

Many water quality problems in England and Wales are caused by discharges from sewage treatment works, industries and farms. In theory, point sources should be easy to control. In practise, a conventional treatment system is likely to be too costly to install and operate, particularly for small businesses which have large debts and marginally profitable concerns. Diffuse pollution from agricultural land and urban storm water run-off has always been difficult to control by conventional methods. Constructed wetlands could be a viable economic option for dealing with wastes from small communities, small industries and farms and diffuse run-off.

The functional benefits of wetlands, whether natural or constructed, are life support, hydraulic buffering and water quality improvement. The important components are water, substrate, vegetation and the microbial community. Variations in type, size and structural arrangement of these can result in a range of wetlands capable of carrying out the basic functions to varying degrees. Natural wetlands may be categorised as bogs, marshes and swamps. Acid bogs and woody swamps are difficult to establish and manage, requiring relatively stable water quantity and quality conditions. Marshes are more flexible in this respect and hence are easier to construct and manage. Nevertheless, excessive waste loading can damage marshes, leading to their destruction and loss of functional benefits.

The majority of constructed wetlands operate as surface flow systems. Substrate flow systems all experience operational problems of rapid clogging and inadequate dissolved oxygen availability for ammonia removal.

Providing that design and construction are correct, effluent quality values of less than 30 mg/l BOD, less than 20 mg/l suspended solids, 10 mg/l ammonia and 50 - 100 faecal coliforms/100 ml should be achieved.

A system for an individual domestic unit, with five people, could be a septic tank discharging to a two cell constructed wetland of 375 ft^2. Discharge from the wetland could be to a watercourse or to ground.

A system for livestock or small community effluent would need a lagoon to achieve initial BOD reduction, followed by a marsh to remove BOD, solids and pathogens. Discharge to a pond would ensure further BOD removal but principally, much of the ammonia removal. However, the pond would probably enable algal blooms to develop, thereby generating increased solids concentrations. These, together with final BOD and ammonia, would be removed by an overland flow cell.

A system to deal with sediment from land run-off or urban storm run-off, and which would also remove nutrients, would need a coarse sediment ditch followed by a grass filter. This is similar to an overland flow cell but has a lower gradient, greater width and a drainage system. This removes fine sediments and some nutrients. Thereafter, a marsh, pond and overland flow cell would operate as for a livestock system.

An approach to dealing with whole catchment problems could be to deal with organic effluent in wetlands adjacent to the source. Nutrient and sediment removal could be achieved by other units just prior to discharge to a river. At strategic sites, larger riparian buffer strips might be able to deal with the output from several farms. Finally, in the lower reaches, a large wetland would provide hydraulic buffering and life support, with limited water quality improvement.

The advantages of constructed wetlands are numerous. Providing that reasonably level ground is available, construction costs are low, about 10 to 50% of those for a conventional plant. Operating costs are also low. There is good performance on BOD, solids and coliform removal, with reasonably good performance on nitrogen and phosphorous removal, allowing compliance with discharge standards. They generate wildlife habitat and recreational space. There is also the potential for educational benefit.

On the debit site, the land requirement is greater than for a conventional system, and the land needs to be more or less level. Steeply sloping land increases the design and construction costs. There is a delay in achieving operational status, at least two growing seasons being required before the system can be working at full capacity. The change of system efficiency with age is unknown, and this may be a disadvantage of considering a large and hence costly system.

The technology of constructed wetlands is still young. Design criteria are being refined as more systems are built and their performance assessed. It is recommended that a comprehensive review of this subject is carried out to identify more clearly the potential benefits of using wetlands to treat small sewage, industrial, agricultural and diffuse discharges.

5.0 CONCLUSIONS

The study tour of US wetlands was extremely useful for a number of reasons.

Seeing the real thing was more informative than reading about it in the literature. Many concepts were more fully understood on seeing them on the ground.

Designers, builders and operators were more forthcoming in face to face discussion than they were in print. We were encouraged by the openness of everyone in talking about their failures as well as their successes.

In the space of a few days we saw a variety of solutions to a wide range of problems. This was essential given the complexity of the unique combination of conditions at Wheal Jane.

By isolating ourselves from other work, and placing ourselves in a forcing environment, we were able to concentrate on one large and complex problem, and to generate some new ideas for its solution. Our understanding of processes, design, engineering and operation of passive systems has been greatly increased, as has our confidence in our ability to develop a satisfactory solution.

Many useful contacts were made, not only in the field of acid mine drainage treatment, but also with regard to environmental law and agricultural pollution control.

Technical conclusions have been incorporated into the final report on passive system evaluation by Arthur D. Little and Marcus Hodges Environment.

Marked route at City of Orlando Wetlands Reclamation Project.

Outfall control and instrumentation at City of Orlando Wetlands Reclamation Project.

Water distribution system at City of Lakeland Wetlands Project.

City of Lakeland Wetlands Project. Collapse due to construction over fine tailings.

Diverse bird community at the City of Lakeland Wetlands Project.

Howe Bridge, Pennsylvania.

Outfall from Anoxic Limestone Drain showing dense precipitate.

REM, Pennsylvania.

Wetland cell under construction with mushroom compost as substrate.

Water distribution system at American

Crystal Sugar Corporation's Wetland Project.

Aerial view of Minot Wetland.

Research cell at "Big 5" Project, Colorado.

Mine water flowing through mushroom compost

and hay mixture.

Central City Mining District, Colorado, showing numerous spoil heaps.